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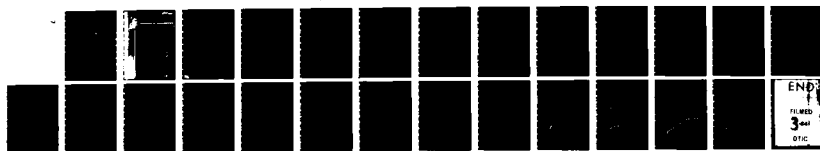
CREEP AND CREEP RECOVERY OF 2618-T61 ALUMINUM UNDER  
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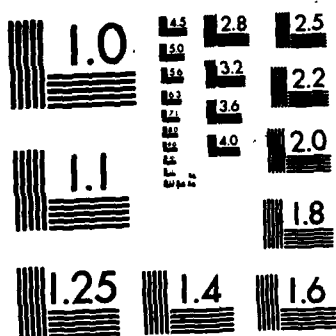
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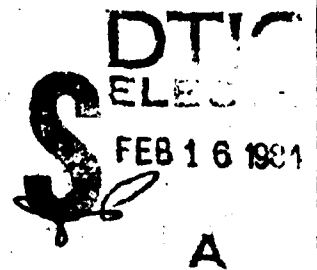
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CREEP AND CREEP RECOVERY OF  
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TEMPERATURE

U.W. Cho and W.N. Findley



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Creep and Creep Recovery of 2618-T61 Aluminum  
Under Variable Temperature

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W. N. Findley\*\*



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### Abstract

Creep and creep recovery data are reported for pure tension of 2618 aluminum alloy under variable temperature between 200°C and 230°C. Varying temperature experiments involved an abrupt temperature increase and a linearly increasing and decreasing temperature at a constant stress of 137.9 MPa (20 ksi). A temperature-compensated time by Sherby and Dorn was employed to represent the effect of temperature. The temperature history dependent theory described the test data quite well for both increasing and decreasing temperature. The apparent activation energy of this alloy was found to be 49,000 cal/mole<sup>K</sup>.

## Introduction

Most creep experiments of metals have been conducted at constant stresses and temperatures. But actual creep problems of structural members involve much more complex conditions such as varying stress and temperature, and gradients in both. As the creep behavior of metals is very sensitive to temperature as well as stress, and creep-controlling mechanisms change with stress and temperature, the proper constitutive relations should account for the effects of stress and temperature together. Since all the creep parameters are possibly affected by temperature, it will not be possible to construct one general relation covering the whole range of stress and temperature. It is desirable to find the simplest equation describing the temperature dependency of creep over a fairly narrow temperature range of practical interest.

In an earlier work by Blass and Findley [1], the creep behavior of 2618 aluminum alloy was reported for abrupt changes in temperature and combined stress states. In a series of works by Findley and Lai [2-4] creep of the same material were reported for variable stresses of combined tension and torsion at 200°C. A viscous-viscoelastic model was developed and extended for variable stresses employing a strain-hardening theory (SH) for nonrecoverable viscous creep components and a modified superposition principle (MSP) for recoverable viscoelastic creep components.

In the present paper, additional experiments on the same lot of material are reported for varying temperature. The temperature effect was incorporated into the original constitutive relation [2,3] by replacing the actual time with an integral form of temperature-compensated time which was first introduced by Sherby and Dorn [5].

Somewhat similar experiments on creep under variable temperature were performed by Mark and Findley on a plastic [6] for which an integral form of reduced time defined by Morland and Lee [7] was employed in the predictions.

#### Material and Specimens

An aluminum forging alloy 2618-T61 was employed in these experiments. Specimens were taken from the same lot of 63.5 mm (2.5 in.) dia forged rod as used in [2-4] and the same as specimens D-H in [1]. Specimens were thin-walled tubes having outside diameter, wall thickness, and gage length of 25.4, 1.52, and 101.6 mm (1.0, 0.060, and 4. in.), respectively. A more complete description of material and specimens is given in [2].

#### Experimental Apparatus and Procedure

The combined tension and torsion creep machine used for these experiments was described in [8] and briefly in [2]. The temperature control and measurement employed was described in [1,2]. The abrupt temperature increase was made manually by increasing the set point of a Thermac temperature controller. For continuously varying temperature, a clock motor and gear train were used to drive the set point of two Thermac temperature controllers at constant rate. One of these Thermacs controlled the power to the heating lamp inside the specimen, and the other controlled the power to both top and bottom end-heaters. The function of the heating lamp and end heaters were described previously [2]. Chromel-alumel thermocouples were used for control and chromel-constantan thermocouples were used for measuring. Stress was produced by applying dead weight at the end of a lever. The weights were applied by manual control of a jack in less than 10 sec. but without shock. For simultaneous temperature increase and loading, the temperature was first

increased to the test temperature just before the load was applied. Similarly for continuously increasing temperature, the clock motor was first started and then the load was applied. The time of the start of the test was taken to be the instant at which the load was fully applied. The gage length employed was measured at room temperature and no correction of gage length was made for thermal expansion.

### Experimental Results

The results of tests D, F, H, K and L are shown in Figs. 1-4. The test data D, F and H were taken from [1], and tests K and L are new.

Figure 1 shows results of creep and creep recovery tests at two different constant temperatures, 200°C (Tests D and H) and 230°C (Test K) under one constant tension stress of 137.9 MPa (20 ksi).

Figure 2 shows results of creep at an abrupt temperature increase from 200°C to 230°C at constant tension stress (Test D), and simultaneous abrupt temperature increase and stress decrease (Test F). The increase in temperature was accomplished in about 20 sec. [1].

Figures 3 and 4 show creep and creep recovery tests (Test L) during which the temperature increased and decreased at a constant rate between 200°C and 230°C, as shown in the temperature curves in Figures 3 and 4.

### Analysis of Data

#### Viscous-Viscoelastic Model

Previous analysis [2] showed that the short time creep of 2618 aluminum alloy at 200°C was well represented by a power function of time such as

$$\epsilon = \epsilon^0 + \epsilon^+ t^n, \quad (1)$$

where  $\epsilon^0$  is the time-independent response,  $\epsilon^+$  is the coefficient of the time-dependent component and  $n = 0.270$  was a constant. By using the creep recovery tests, the time-dependent component was separated into recoverable and nonrecoverable components, and  $\epsilon^0$  was found to be elastic strain with negligible plastic strain.

Eq. (1) may be rewritten as

$$\epsilon = \epsilon^E + \epsilon^{+VE}t^n + \epsilon^{+V}t^n, \quad (2)$$

where  $\epsilon^E$  is elastic strain and  $\epsilon^{+VE}$  and  $\epsilon^{+V}$  are the recoverable viscoelastic strain coefficient and the nonrecoverable viscous strain coefficient, respectively.

The ratio  $r = \epsilon^{+VE}/\epsilon^{+V} = 0.55$  was a constant over the stress range considered. Then,  $\epsilon^{+VE} = \epsilon^+r/(1+r)$ , and  $\epsilon^{+V} = \epsilon^+/(1+r)$ . The stress dependence of  $\epsilon^+$  was represented by a third order multiple integral representation [9] as

$$\epsilon^+ = F(\sigma - \sigma^*) = F_1(\sigma - \sigma^*) + F_2(\sigma - \sigma^*)^2 + F_3(\sigma - \sigma^*)^3, \quad (3)$$

where  $\sigma^*$  is the apparent creep limit below which negligible creep was assumed. Subsequent work [10] has shown that creep does occur at stresses below the apparent creep limit. The values of  $F_i$  and  $\sigma^*$  were determined in [2], and are a function of temperature.<sup>1</sup>

#### Effect of Temperature

The temperature effect was incorporated in this paper by employing the temperature-compensated time, introduced by Sherby and Dorn [5] as

$$\theta = \int_0^t [e^{-Q/RT(s)}] ds, \quad (4)$$

where  $Q$  is the apparent activation energy,  $R$  is the gas constant ( $= 1.986 \text{ cal/mole}$ ).  $T$  is absolute temperature ( $^{\circ}\text{K}$ ), and  $s$  and  $t$  are previous and current time, respectively. Then creep under variable temperature can be described by replacing  $t$  with  $\theta$  in Eqs. (1)-(3). In [11] Dorn and Jaffe showed Eq. (4) to be applicable over a wide temperature range. At a constant temperature Eq. (1) may be rewritten as

$$\epsilon = \sigma/E(T) + C[e^{-Q/RT} t]^n, \quad (5)$$

where  $E$  is Young's modulus as a function of temperature. Comparing with Eq. (1) and (5)  $\epsilon^+ = Ce^{-nQ/RT}$ , where  $C$  is now a function of stress only as

$$C = F'(\sigma - \sigma^*) = F'_1(\sigma - \sigma^*) + F'_2(\sigma - \sigma^*)^2 + F'_3(\sigma - \sigma^*)^3, \quad (6)$$

where the creep limit,  $\sigma^*$  was assumed to be constant. Then the values of  $F'_i$  may be computed from  $F_i$  by dividing by  $e^{-nQ/RT}$ .

#### Determination of Activation Energy, $Q$

Assuming that  $Q$  is constant between  $200^{\circ}\text{C}$  and  $230^{\circ}\text{C}$  the values of  $Q$  may be determined from creep tests at the same stress but under two different temperatures as follows. From Eq. (5),

$$\ln(\epsilon_1^+/\epsilon_2^+) = -\frac{nQ}{R} \left[ \frac{1}{T_1} - \frac{1}{T_2} \right]. \quad (7)$$

Test data of D1, H1 and K1 shown in Fig. 1 were fitted to Eq. (1) by least squares with  $n = 0.270$ . For 200°C the average of D1 and H1 was used, as  $\epsilon^0 = 0.2109\%$ ,  $\epsilon^+ = 0.019217\%/h^n$ . For 230°C, K1 yielded  $\epsilon^0 = 0.2147\%$ ,  $\epsilon^+ = 0.044604\%/h^n$ .

Using these values, the creep curves were computed and are shown as solid lines in Fig. 1. The apparent activation energy was calculated from Eq. (7) as  $Q = 49,000$  cal/mole°K. From this value the  $F'_1$  in Eq. (6) were recalculated by separating the temperature effect as  $F'_1 = 5486.0\%$  per ksi- $h^n$ ,  $F'_2 = -462.0\%$  per ksi<sup>2</sup>- $h^n$  and  $F'_3 = 32.56\%$  per ksi<sup>3</sup>- $h^n$ .

The activation energy was also calculated from two experiments in [1] in which the temperature was changed abruptly in about 20 sec. during a creep test. Using the Dorn-Jaffe method [11] for test D1-D2, an increase in temperature from 202°C to 228°C at a tensile stress of 137.9 MPa (20 ksi), yielded  $Q = 45,000$  cal/mole°K. Test D3-D4 involved a decrease in temperature from 228°C to 203°C at a constant combined stress of 137.9 MPa (20 ksi) tension and 79.3 MPa (11.5 ksi) torsion. A value of  $Q = 50,000$  cal/mole°K was found from these data. These results compare well with the present determination from creep at two different temperatures.

#### Change of Young's Modulus, E

The Young's modulus was determined in [2] as  $E = 9.43 \times 10^6$  psi at 200°C. The result of test K1 at 230°C showed that the elastic strain increased and thus E decreased as temperature increased. With assumptions of no plastic strain and a linear variation of E with temperature between 200°C and 230°C, the following relation was obtained.

$$E(T) = (11.164 - 0.003666 T) \times 10^6 \text{ psi}, \quad (8)$$

where T is absolute temperature (°K).

The creep curves as recalculated by Eqs. (5), (6) and (8), are shown as dotted lines in Fig. 1.

### Creep Recovery

Creep recovery was described by using the superposition principal (see [9]) as

$$\epsilon = \epsilon^{+V} t_1^n + \epsilon^{+VE} \{t^n - (t-t_1)^n\}, \quad (9)$$

where  $t_1$  is the time at which the stress was removed. Employing  $\theta$  as in creep, Eq. (9) may be rewritten as

$$\epsilon = A \theta_1^n + B \{\theta^n - (\theta - \theta_1)^n\}, \quad (10)$$

where  $\theta_1 = \int_0^{t_1} e^{-Q/RT(s)} ds$ .

At constant temperature Eq. (10) becomes for pure tension

$$\epsilon = \frac{1}{1+r} C e^{-nQ/RT} \{t_1^n + r[t^n - (t-t_1)^n]\}, \quad (11)$$

where C is a function of stress as in Eq. (6),  $A = C/(1+r)$  and  $B = Cr/(1+r)$ .

In order to check the applicability of Eqs.(9)-(11) at different temperatures, Eq. (9) was fitted to the creep recovery data of H2 and K2; and  $\epsilon^{+V} t_1^n$  and  $\epsilon^{+VE}$  were determined by least squares using  $n = 0.270$  as follows:

$$\text{H2: } \epsilon^{+V} t_1^n = 0.0139\%, \quad \epsilon^{+VE} = 0.006219 \% / h^n,$$

$$\text{K2: } \epsilon^{+V} t_1^n = 0.0324\%, \quad \epsilon^{+VE} = 0.014783 \% / h^n.$$

These values and Eq. (9) resulted in the recovery curves shown as solid lines as in Fig. 1. Also from the previous results of  $\epsilon^+$ , the values of  $\epsilon^{+V}$  were calculated by  $\epsilon^{+V} = \epsilon^+ - \epsilon^{+VE}$ . The ratio  $r$  was calculated as  $r = 0.50$  at  $200^\circ\text{C}$  and  $r = 0.48$  at  $230^\circ\text{C}$ , which was close to  $r = 0.55$ , previously determined from several different stress levels at  $200^\circ\text{C}$ . Thus  $r = 0.55$  may be suitable for the temperature range between  $200^\circ\text{C}$  and  $230^\circ\text{C}$ . In the following calculations  $r = 0.55$  was adopted as before. Recovery curves recalculated by Eq. (11) are shown as dotted lines in Fig. 1.

### Creep Under Variable Temperature

The temperature-compensated time,  $\theta$ , as a form of Eq. (4), includes the effect of previous temperature history up to the current time,  $t$ . Thus the temperature history dependent theory (THD) for creep under variable temperature may be formulated as

$$\epsilon = \sigma/E(T) + \alpha_L(T-T_1) + C \left[ \int_0^t e^{-Q/RT(s)} ds \right]^n, \quad (12)$$

where  $\alpha_L$  is a linear thermal expansion coefficient,  $T_1$  is a reference temperature, and the other parameters have the same meaning as in the previous section. For comparison, a temperature history independent theory (THI) was formulated as

$$\epsilon = \sigma/E(T) + \alpha_L(T-T_1) + C [e^{-Q/RT_t}]^n, \quad (13)$$

which states that the total creep strain or creep rate is a function of the current temperature only.

### Prediction of a Step Increase in Temperature

By a step increase in temperature to 228°C without change of stress following creep at 137.9 MPa (20 ksi) and 202°C, there may occur an instantaneous increase in axial strain from two different sources, as indicated by Eq. (12) or (13). One is the thermal expansion and the other is change of elastic strain by change of Young's modulus with temperature. Then, the net change of strain may be calculated as

$$\Delta\epsilon = \Delta\epsilon^E + \Delta\epsilon^T = \left[ \sigma_2/E(T_2) - \sigma_1/E(T_1) \right] + \alpha_L(T_2 - T_1) \quad (14)$$

where  $\sigma_2 = \sigma_1$  for test D Fig. 2, and the linear thermal expansion coefficient was determined from a small incremental temperature test after the creep recovery period in Tests K and L as  $\alpha_L = 1.365 \times 10^{-3}\%/^{\circ}\text{F}$  between 200°C and 230°C.

As the time independent strain change was too large to be properly included in one plot, the strain change,  $\Delta\epsilon = 0.0662\%$  was subtracted from data of test D2 and from the predictions by Eq. (12) or (13) for test D2. The (THD) curve by Eq. (12) was shown as solid lines and the (THI) curve by Eq. (13) was shown as dotted lines in Fig. 2.

### Prediction of Simultaneous Increase in Temperature and Decrease in Stress

Test F involved a simultaneous increase in temperature (200°C → 230°C) and decrease in stress (172.4 MPa (25 ksi) → 122.0 MPa (17.7 ksi)). The calculation of period F1 for (THD) and (THI) are the same either by Eq. (12) or (13). The prediction of creep during period F2 was calculated by the modified viscous-viscoelastic (MVV) theory [3,4] as

$$\epsilon^V = \{ [F^V(\sigma_1)]^{1/n} \theta_1 + [F^V(\sigma_2)]^{1/n} (\theta - \theta_1) \}^n, \quad (15)$$

and  $\epsilon^{VE}$  was frozen since the amount of stress decrease was less than the creep limit ( $\sigma^* = 13.26$  ksi). See [3] for details. Also the net instantaneous strain change was calculated by Eq. (14) as  $\Delta\epsilon = -0.0015\%$ . The (THD) curves determined by Eq. (12) and (15) are shown as solid lines and the (THI) curves by Eq. (13) and (15) are shown as dotted lines in Fig. 2.

#### Prediction of Linearly Increasing and Decreasing Temperature

Test L involved a linearly increasing and decreasing temperature during creep and during creep recovery periods as shown in Fig. 3 and 4. The temperature data in  $^{\circ}\text{C}$  were fitted to the following four piecewise linear equations

$$\begin{aligned} T_1(t) &= 200.3 + 11.976 t, & 0 < t \leq 2.5 \\ T_2(t) &= 262.2 - 12.826 t, & 2.5 < t \leq 4.8 \\ T_3(t) &= 140.7 + 12.518 t, & 4.8 < t \leq 7.2 \\ T_4(t) &= 317.6 - 12.143 t, & 7.2 < t \leq 9.6 \end{aligned} \quad (16)$$

These equations are drawn as solid lines in Fig. 3 and 4. For the creep period (test L1), the (THD) or (THI) curve was calculated by Eq. (12) or (13), and shown as solid lines or dotted lines, respectively. Another plot of the data and predictions showing creep only was made by subtracting the thermal expansion from both data and theory. Also for comparison the predictions without change of elastic strain are shown as dash lines for (THD) curves and dash-dot lines for (THI) curves. In all the foregoing calculations the reference temperature was taken as the starting test temperature just before loading.

For creep recovery (test L2), the (THD) curves were calculated by Eq. (10) with and without thermal expansion and are shown as solid lines in Fig. 4. The (THI) curve was calculated by Eq. (11) with and without thermal expansion and shown as dotted lines in Fig. 4. In this plot, the disagreement between the (THI) curve and data was too large to be included in the same plot. So all the data and theory curves were drawn to be matched at the time of the first data point. Also the reference temperature was taken as the same one as in the creep period ( $T_1 = 200^\circ\text{C}$ ).

#### Discussion of Results

In Fig. 1, creep curves at  $200^\circ\text{C}$  (D1 and H1) were well represented by using  $n = 0.270$  in Eq. (1). But at  $230^\circ\text{C}$  (K1) using  $n = 0.270$  caused a slight deviation from the data, and the deviation would become bigger as time increased. The best fit curve to (K1) resulted in  $n = 0.398$ , which suggested that the power  $n$  might be a function of temperature.

The creep recovery curves are well represented by using  $n = 0.270$  in Eq. (9) for both at  $200^\circ\text{C}$  and  $230^\circ\text{C}$ , which suggests that the recoverable viscoelastic strain takes the transient type creep with a constant power  $n$ .

In Fig. 2, creep at an abrupt temperature increase with no change of stress, as in test D1-D2, was quite well predicted by the (THD) equation. But the (THI) equation caused a jump in creep strain upon a step change in temperature, which is clearly an unreasonable prediction. For creep with a simultaneous stress drop and temperature increase, as in Test F1-F2, both the (THD) and (THI) equation predicted a much lower creep rate than the test data. This prediction might be improved by including the creep below the creep limit as found in [10], and also by considering a change of the creep limit in Eq. (6) similar to the change of yield limit with temperature [11].

In Fig. 3, creep under linearly increasing and decreasing temperature was reasonably well described by the (THD) equation. Consideration of a change in the elastic strain with increasing temperature improved the prediction, but for decreasing temperature the curves without change of elastic strain (dash lines) gave a better prediction of creep rate than considering the change.

The prediction of recovery curves in Fig. 4 shows similar trends to the creep in Fig. 3. The predicted recovery rate was less than the test data. Obviously the results indicated that the (THI) equations are not applicable for creep under variable temperature.

#### Conclusions

1. A viscous-viscoelastic model with a replacement of a temperature-compensated time for the actual time described creep and creep recovery under variable temperature quite well.
2. The apparent activation energy of 2618 T61 aluminum alloy was determined to be 49,000 cal/mole<sup>o</sup>K between 200<sup>o</sup>C and 230<sup>o</sup>C.
3. Creep under an abrupt change in temperature or a linearly increasing and decreasing temperature at constant stress was reasonably well described by a temperature-history dependent theory.

4. Creep under changes in both stress and temperature requires more detailed informations about temperature dependence on creep parameters.

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Figure Captions

- Fig. 1 Creep and creep recovery of 2618-T61 Al under pure tension of 137.9 MPa (20 ksi) and at 200°C (D1, H1 and H2), and at 230°C (K1 and K2). Use ordinate scale on the left for creep and on the right for creep recovery.
- Fig. 2 Creep of 2618-T61 Al under an abrupt temperature increase with a simultaneous decrease of stress (F1-F2), and without a stress change (D1-D2)
- Fig. 3 Creep of 2618-T61 Al under linearly increasing and decreasing temperature between 200°C and 230°C at a constant tension of 137.9 MPa (20 ksi).
- Fig. 4 Creep recovery of 2618-T61 Al under linearly increasing and decreasing temperature between 200°C and 230°C following the creep period shown in Fig. 3 at a constant tension of 137.9 MPa (20 ksi).

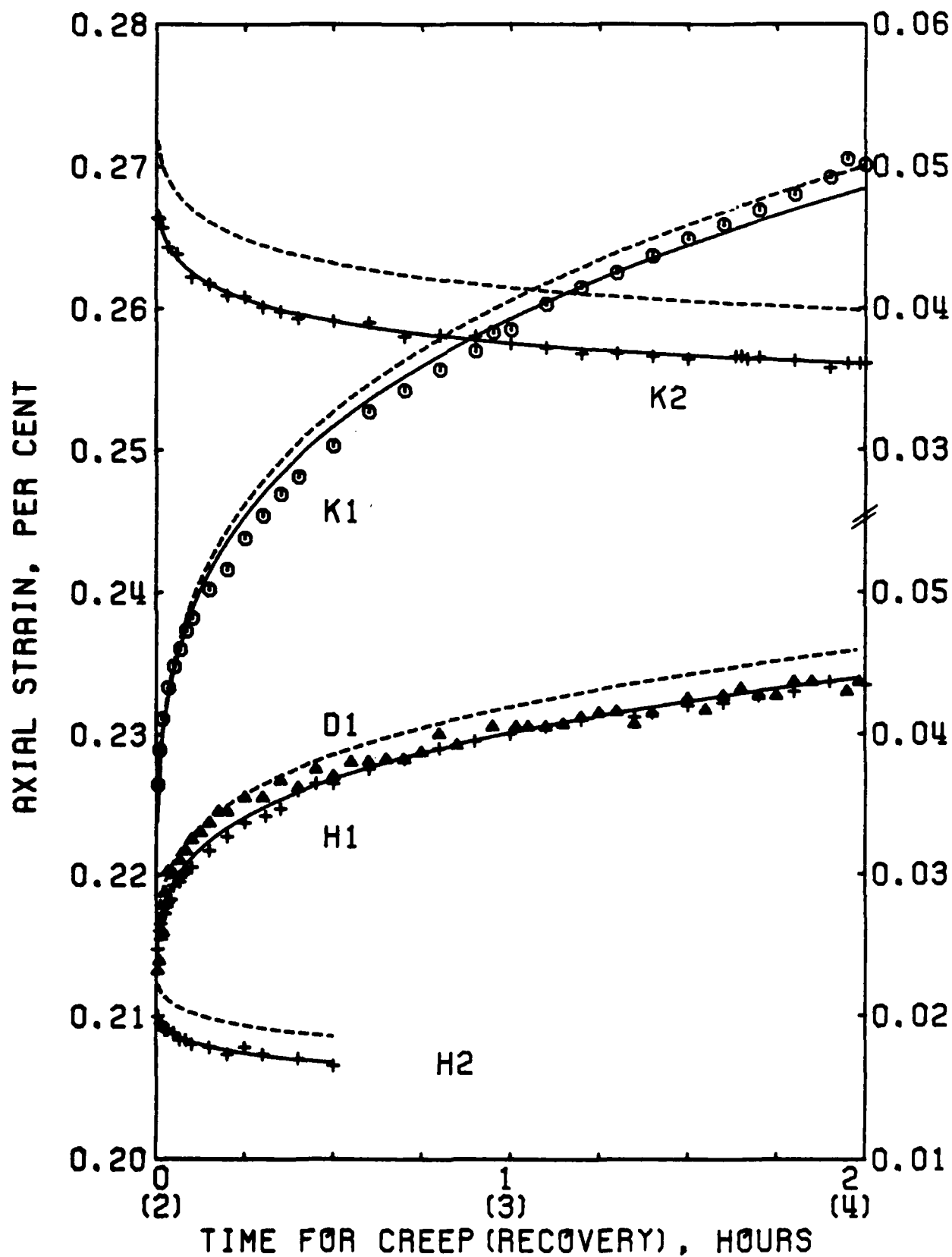


Figure 1.

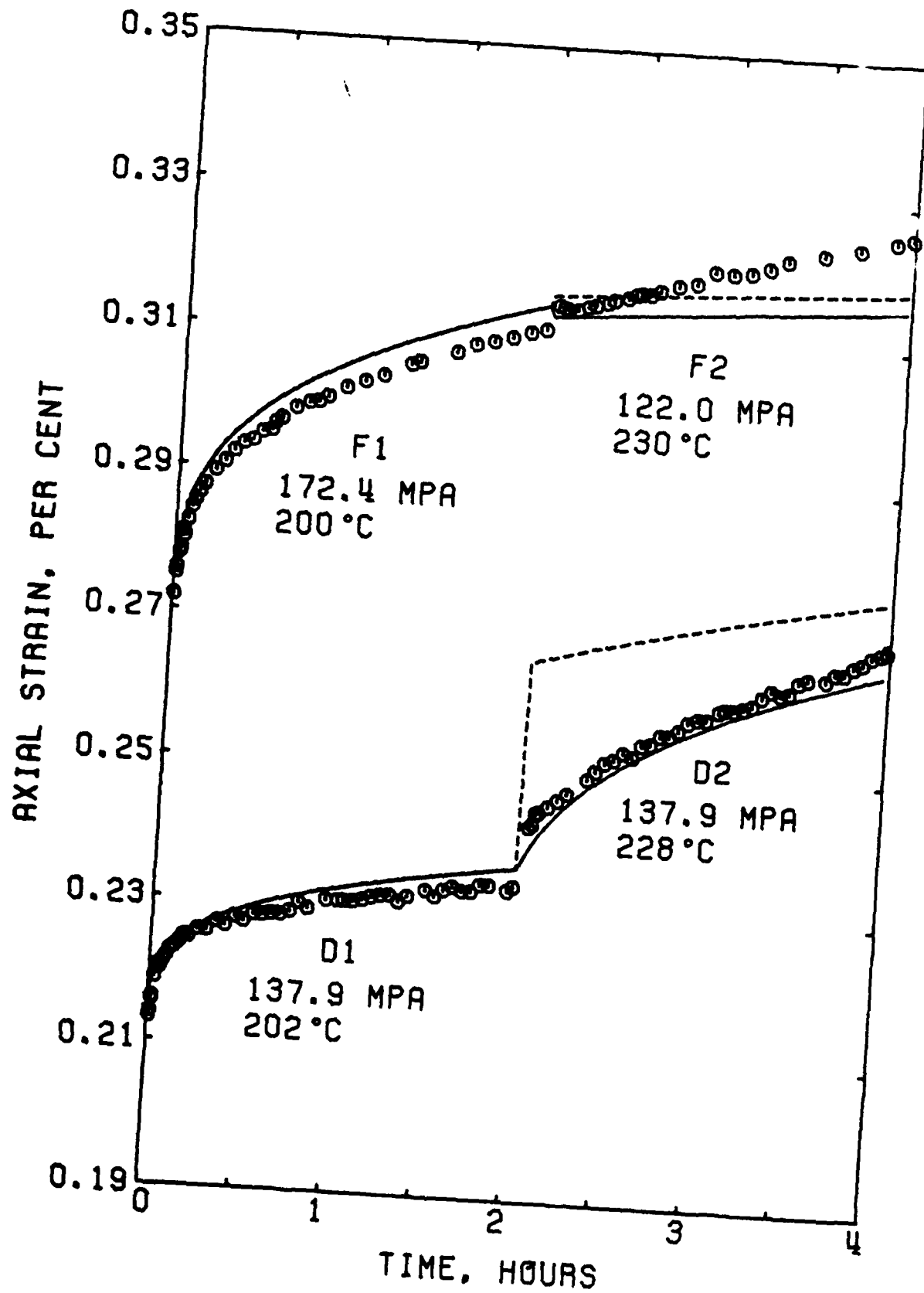


Figure 2.

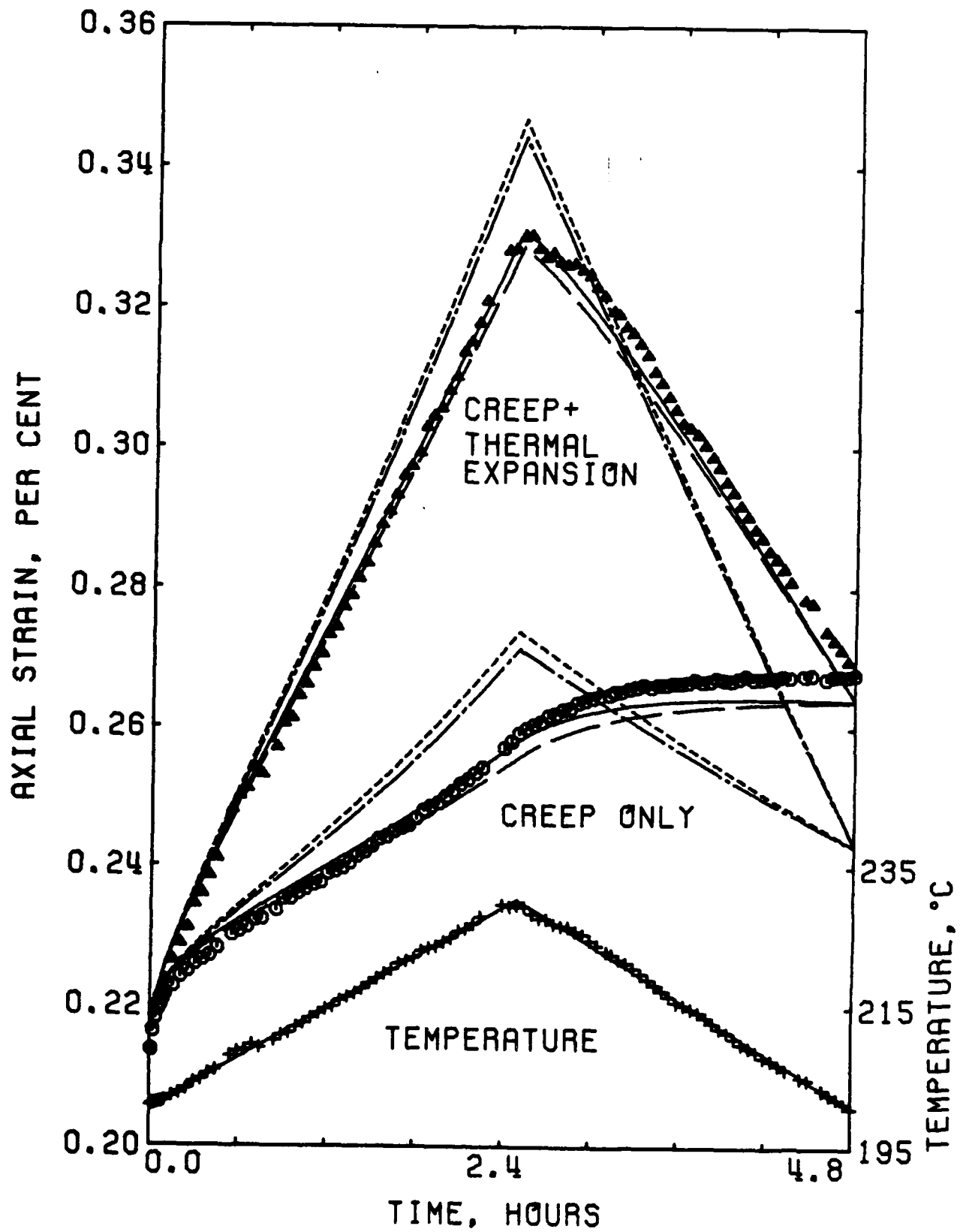


Figure 3.

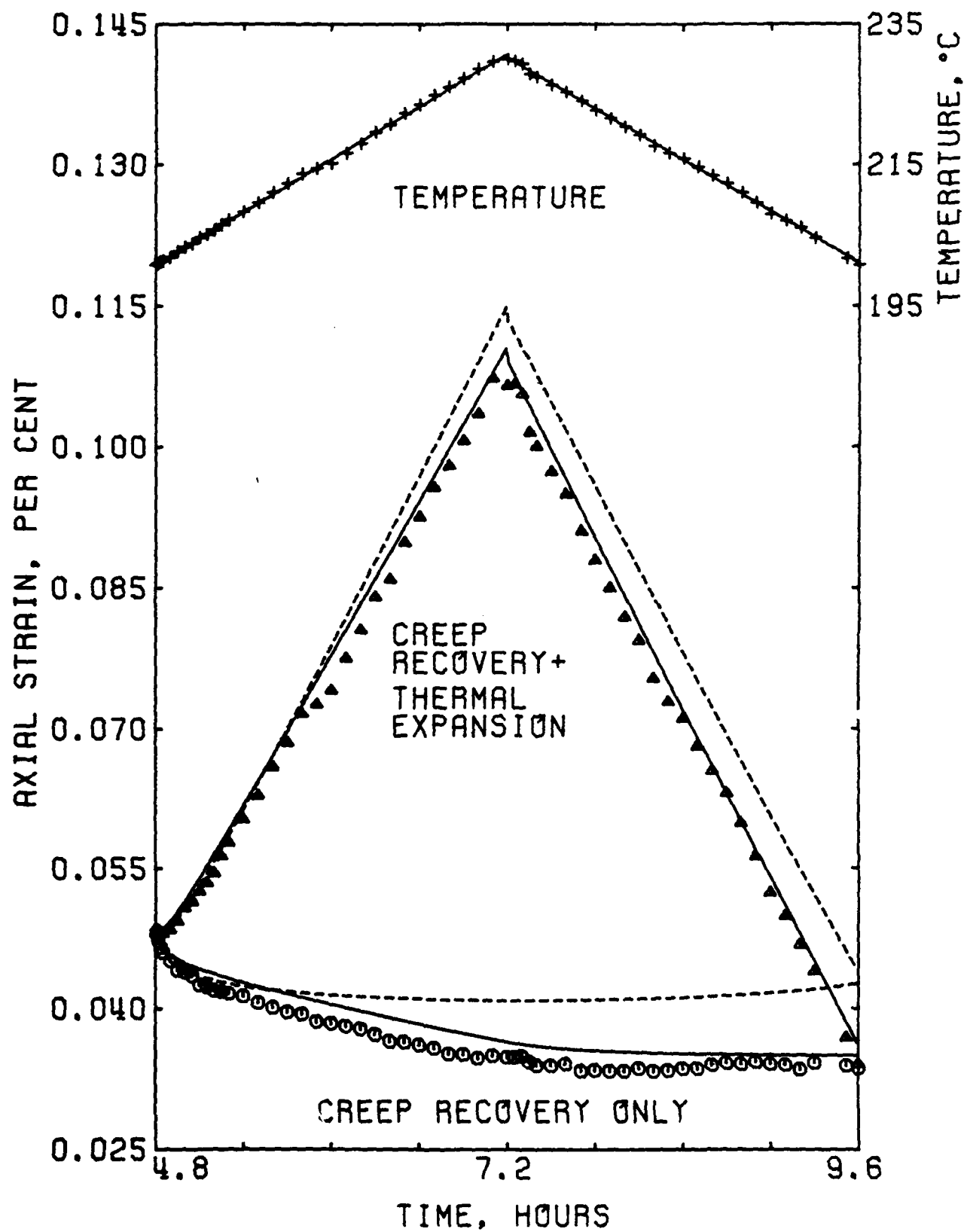


Figure 4.

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